MICROWAVE PROPAGATION MEASUREMENTS IN THE LOW ALTITUDE REGION USING SINGLE FREQUENCY AND WIDEBAND SYSTEMS

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1. ABSTRACT

Low altitude microwave propagation is a dominant factor in the detection and tracking of low flying cruise missiles by shipboard naval radars. Significant temporal and spatial fluctuations in microwave propagation loss have been observed in the lower ten meters above the sea surface. In order to better understand these fluctuations and to support the design and test of future naval radars, two systems were developed which allowed the direct measurement of microwave propagation loss. One system measured propagation pathloss versus range at a single frequency either at Ku or X band, while the other system measured propagation pathless versus time at a fixed range for frequencies in the 2-18 GHz band. The receivers were located at fixed heights commensurate with shipboard radar heights and the transmitters simulated low flying target heights of 3 to 39 feet.

A selected set of the data collected both on the Potomac River near the Naval Surface Warfare Center in Dahlgren, VA and at the NSWC Detachment in Wallops Island, VA is shown to illustrate some of the unique insight gained through these measurements. The information obtained from the collected data has been and continues to be used in sensor design and specification, and can be directly applied to the acquisition of sensors. Installation of a 2-18 GHz measurement system on a boat further enables a study of propagation effects versus range over a wide frequency band at a high temporal update rate. The measurement capability and the resulting database can serve the Navy with great value in areas such as supporting Combat Ship System Qualification Trials (CSSQT), land based testing of developmental sensor systems, radar design and development, and operational testing.

2. INTRODUCTION

Microwave propagation at low altitudes is strongly affected by the structure of the refractive index of the lower atmosphere. Microwave propagation in this region, especially down at 10 meters above the sea surface, has long been known to vary with altitude, range, time and frequency. Under subrefractive conditions, the radar horizon may be significantly reduced. Under enhanced propagation conditions (ducting), deep nulls have been both predicted and observed with widths less than 3 feet in altitude, and having varying, and inadequately defined, temporal and spatial characteristics. A number of threats have been designed to take advantage of this low altitude region. Testing of developmental sensor systems in this complicated low altitude propagation region is confronted by the difficulty of achieving enough test runs over broad environmental conditions to adequately quantify system performance. The performance of the radar can vary significantly on a given day. These propagation induced variations often overshadow other important parameters such as target radar cross section.

The parabolic equation-based microwave propagation models using the refractive index profiles as input are relatively accurate when adequate profiles are available along the propagation path. However, adequate sampling of these refractive profiles can be difficult to obtain. Thus, to accurately assess the performance of a sensor system, it is necessary to make a direct microwave propagation measurement. In order to provide key input to future sensor requirements and design, and to support performance testing and evaluation of existing systems, two direct microwave measurement systems were developed. One system operated at a single frequency in Ku or X band, and the other system covered 2 to 18 GHz frequency range at a high temporal update rate. Analysis performed during the NATO AAW program indicated that unique propagation effects such as the horizontal fade were most evident in the X to Ku frequency bands (Ref. 1). Therefore, the initial single frequency measurements were made at Ku band to enhance the likelihood that these propagation effects would be detected. The single frequency measurements focused on X band in the summer of 1995 in support of joint testing with the Naval Research Laboratory's Naval Engagement -- Radar.

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3. MEASUREMENT SYSTEMS

3.1 Single Frequency System (SFS)

5.1 Single Frequency System (SFS)

5.1.1 Horizontal Fade

A phenomenon called *"horizontal fade"* has been both predicted and measured experimentally (Ref. 1). From the data collected at the NSWCDD Potomac River test location, this effect is clearly shown. Figure 1 illustrates the data in a coverage diagram format with propagation factor relative to freespace shown using a gray scale. The horizontal axis shows the range as determined by GPS, and the vertical axis represents the height of the target.

The propagation profile plot of Figure 1 shows a fade region where the propagation factor is 20 to 25 dB below freespace which persists at a constant altitude versus range. Just above and below this horizontal fade, there is an enhancement in propagation of 5dB better than freespace. So for a target crossing these regions, a two-way system sensor would experience 50 to 60 dB of signal fluctuation from propagation alone. The enhancement of propagation just above the surface will increase the surface clutter, further reducing the ability to detect and track the target.

The lower subplot in Figure 1 shows propagation model output for a 92 ft duct which was consistent over the range covered. The Personal Computer Parabolic Equation Model (PCPEM) (Ref. 2) was used for all modeled data in this report. The refractive profile used to model this duct is shown in Figure 2. The modeled data also indicates the horizontal fade at the same approximate location and shows relatively good agreement with the measured data. The horizontal fade was observed on several occasions.

5.1.2 Multi-Modal Propagation

Evidence of a surface-based duct is depicted by the data shown in Figure 3. This data was collected at the Wallops Island test location. In the upper subplot of Figure 3, a definite change in the propagation structure at approximately 15 nmi can be seen. Smooth transitions between different propagation factors in the nearer ranges show a standard atmosphere or low evaporation duct characteristic. The multi-modal interference characteristics are evident beyond 15 nmi. The lower subplot in Figure 3 shows the model output for the refractive profiles collected by the helicopter. The time and radial coincidence of the refractive profile data and the measured propagation factor data was quite good. Although the nature of the propagation characteristic agrees, the range of the transition is approximately 18 nmi versus the 15 nmi in the upper subplot. The model output also indicates larger propagation factors overall and shows the bending downward of the destructive interference region at closer range and lower height than the measured propagation data. The reason for this discrepancy is not known, but it does point out that even with good temporal and spatial correlation between meteorological data collection and micro wave measurements, there can be significant differences in the propagation factors generated from each.

Figure 4 shows the refractive profiles that were used as input to the propagation model which generated the data shown in the lower subplot of Figure 3. These refractive profiles were preprocessed using a program called LARRI (Large-Scale Atmospheric Refractivity Range Interpolator) which smoothes and prepares measured meteorological data for use by propagation models. LARRI was developed by the Johns-Hopkins University Applied Physics Laboratory for use with their helicopter-based meteorological measurements (Ref. 3).

5.1.3 Subrefraction

On several occasions the SFS data collected at the Wallops Island location indicated a subrefractive environment. One example of a subrefractive case is shown in Figure 5. The black regions in the upper subplot represent data points that were discarded when the boat was unable to maintain proper alignment with the receiver. If more than 1 dB of antenna gain loss could have been incurred, the data was not used in the resulting plot. Since the boat's heading was recorded using a digital compass, and the bearing was available from GPS, a filter could be used to reject these measurements. The modeled and measured data match reasonably well in this case. The refractive profile used in the model is shown in Figure 6. The refractive data was collected as a function of range on nearly the same radial the boat traveled and at nearly the same time.

5.1.4 Data Summary

Considering only the 13.95 GHz SFS data (no examples of the 9.5 GHz data are shown in this report), the horizontal fade was measured on two days at NSWCDD Potomac River and perhaps once to a lesser degree at Wallops Island. Three other days at NSWCDD Potomac River also showed some evidence of the *horizontal fade*. Several other characteristics of multimode propagation were also sensed by the system during periods of ducting that were dominated by surfaced-based ducts rather than the evaporation duct. During these periods, a high degree of variability in the propagation factor versus range and altitude (and most likely also time) was sensed by the system. Seventeen test days were covered at two locations during two seasons of the year (6 at NSWCDD and 11 at Wallops Island). Some degree of ducting or enhanced propagation was exhibited during all but three of the days. On the three days that did not exhibit ducting, a subrefractive environment was indicated. All of the subrefractive days were measured at Wallops Island. The data set is not large enough to draw statistical conclusions about the percentage occurrence of ducting or subrefraction. However, the fact that such a range of conditions was sensed over a relatively short period of time indicates that the propagation environment is quite dynamic and can easily dominate sensor performance. Many of the ducting environments exhibited spatial variations in one-way propagation factor as large as 30 dB. That would significantly effect sensor performance, depending on the location of the target in height and range.

In general, the model predictions made using the best refractive profile data with respect to time and radial coincidence with the microwave measurements, yielded reasonable agreement at least with regard to trends. Most notable were the good comparisons between measured and predicted *horizontal fade* situations. In the case of some of the more complicated refractive environments, exact matches seem out of reach, perhaps due to the temporal variability present in the refractive environment.

5.2 Microwave Propagation Measurement System

5.2.1 Temporal Variability

Both long and short term temporal variability were observed during the data collection period. The long term variability was marked primarily by a transition from ducting to subrefraction and vice versa. Figure 7 shows an example of such a transition from ducting to subrefraction. The propagation factors are plotted for four different frequencies for the receiver at 54 feet. In Figure 7 the four horizontal bands depict the measured propagation factors at four frequencies. The horizontal axis shows the time span of approximately 12 hours. The vertical axes for each of the four frequencies represent target heights. The propagation factors relative to freespace are plotted in gray scale. Two-minute periods where the data was not taken are shown as gray vertical stripes. At 0600 hours, a wide stripe of gray is shown when the system was off-line.

The earlier part of the time period covered in Figure 7 indicates enhanced propagation factors better than 10 dB above the freespace. At higher frequencies strong null structures can be seen versus target altitude. A helicopter sounding taken about 30 km off the coast of Wallops Island showed a surface duct up to about 50 meters about five hours (2002 UTC, Mar 23) prior to the beginning of the time period covered in Figure 7. On March 23 at 1800 UTC, a surface pressure chart showed that the Wallops Island area was within a warm maritime tropical air mass associated with a high pressure center located near Bermuda. There were no fronts within 300km of Wallops Island (Ref. 4).

Around 0600 UTC on March 24, the transition from strong ducting to subrefraction occurred. The transition took approximately 2 hours, and subrefractive conditions lasted for over twenty hours. During the subrefractive period, the highest sensor showed least loss of the four, but all frequencies performed poorly. Weather data shows at 1200 UTC on March 24, a warm front lying just north of the Wallops Island area. A helicopter sounding, taken on March 24 at 1508 UTC about 18km off the coast of Wallops Island, showed subrefractive conditions below 90 meters (Ref. 4). Unfortunately, during the time of transition, no local weather data were available and no helicopter or boat meteorological data were available because of the time of the day. However, the timing of this fade transition was compared to the data from a C-band link operated by APL along a similar path (Ref. 5) and showed a good agreement.

The line plot in Figure 8 shows an example of a highly variable propagation which occurred over a short period of time. This short term variability occurred primarily during periods when a ducting environment was present. In Figure 8 the propagation profiles are shown for four different frequencies for the receiver height of 84 feet. The horizontal axes show the one-way propagation factor relative to the freespace in dB, and the vertical axes show the target heights. The overlapped traces represent eight minutes of collected data and display a large degree of variability in propagation factor. Since each frequency was revisited every 8 seconds, sixty samples are displayed. Significant changes in the null height and depths, 20 to 30 dB, can be seen. This rapid and large variability (as much as 60 dB for a two-way radar system) could have a significant impact on the performance of a radar depending on its threshold and track filter characteristics.

5.2.2 Frequency Effects On Null Filling

Much of the data collected are useful in analyzing the percentage bandwidth necessary to reduce or “fill in” the null structures in the pathless profiles created by multimode propagation in ducting environments. The data in Figure 9 shows four different frequencies, 5.9, 8.475, 13.57, and 17.35

GHz, for the receiver at 54 feet. It shows a shift in null heights with a change in frequency as well as a change in the number of nulls. The lowest frequency shown in Figure 9 appears to have the best overall loss performance and no huge null structures. These effects or null structures also occur with range changes which could not be measured during this test because the transmit and receive arrays were at fixed locations,

5.2.3 **Data Summary**

In general, the mid frequency range of 5.9 to 12.3 GHz showed the least loss over all conditions and least variability with time and transmitter height. Best performance versus sensor height depended on the environment type. Under some strong ducting conditions, the lower sensors showed the least loss. In other situations, higher sensors showed less loss.

Considering all the data collected over the test period, propagation worse than the 4/3 earth (subrefraction) occurred between 20 to 60 % of the time depending on geometry and frequency. Figure 10 shows the histogram of propagation factor values over the entire test period for 3.6 GHz (receiver at 54 feet and target at 15 feet). The data indicate that 42% of the propagation data was worse than 4/3 earth, or subrefractive. This shows that, at least for the period of the four months covered by these tests, subrefraction occurred a significant portion of the total test time.

6. SYSTEM UPGRADE

There is a current effort to install both the SFS and the MPMS on the boat, *Sea Lion,* to further our ability to characterize propagation effects by covering a wide frequency band vs. range. This would allow a capability to measure propagation across 2 to 18 GHz versus range with a very rapid temporal update rate.

7. CONCLUSION

The measurements of RF propagation in this report have shown that the propagation environment varies significantly with altitude, range, time and frequency in the low altitude region. Over 15 dB of variation in one-way propagation loss was observed for target height differences of 3 feet, or time periods of less than 20 seconds. This variation would be doubled for a two-way system like a radar. Longer term variations from ducting to subrefractive environments that resulted in a 40 dB change in one-way loss were also observed. These subrefractive environments lasted over thirty hours in some cases, and the loss values were essentially frequency-independent over the 2 to 18 GHz band. Only increasing the height of the radar receiver showed any decrease in pathloss during these subrefractive environments. The data indicate that under many of the extreme environments, the performance of the conventional narrowband radars will vary significantly against sea-skimming threats. The data also show that having a sensor with a wideband capability could improve propagation related performance by 20 to 30 dB. Subrefractive conditions occurred a significant percentage of the total test period.

The information obtained from the collected data should be useful for sensor design and specification. With the development of two direct microwave propagation systems, the Single Frequency System and the Microwave Propagation Measurement System, it is possible to validate many of the propagation models and make ground truth measurements for radar test observations. The data discussed could be used for remote sensing in terms of the development of refractivity inversion techniques (Ref. 6).

These two systems, could and should be used to support the operational and engineering testing of ship combat systems. In events such as Combat Ship System Qualification Trials (CSSQT) where assessment of true performance of sensor systems is critical, the SFS and MPMS could play a vital role. Utilization of the unique capability of the MPMS to measure propagation for low elevation targets with fine height and frequency resolution covering most of the shipboard radar frequency band, provides invaluable input to the design of future Navy radars.

8. REFERENCES

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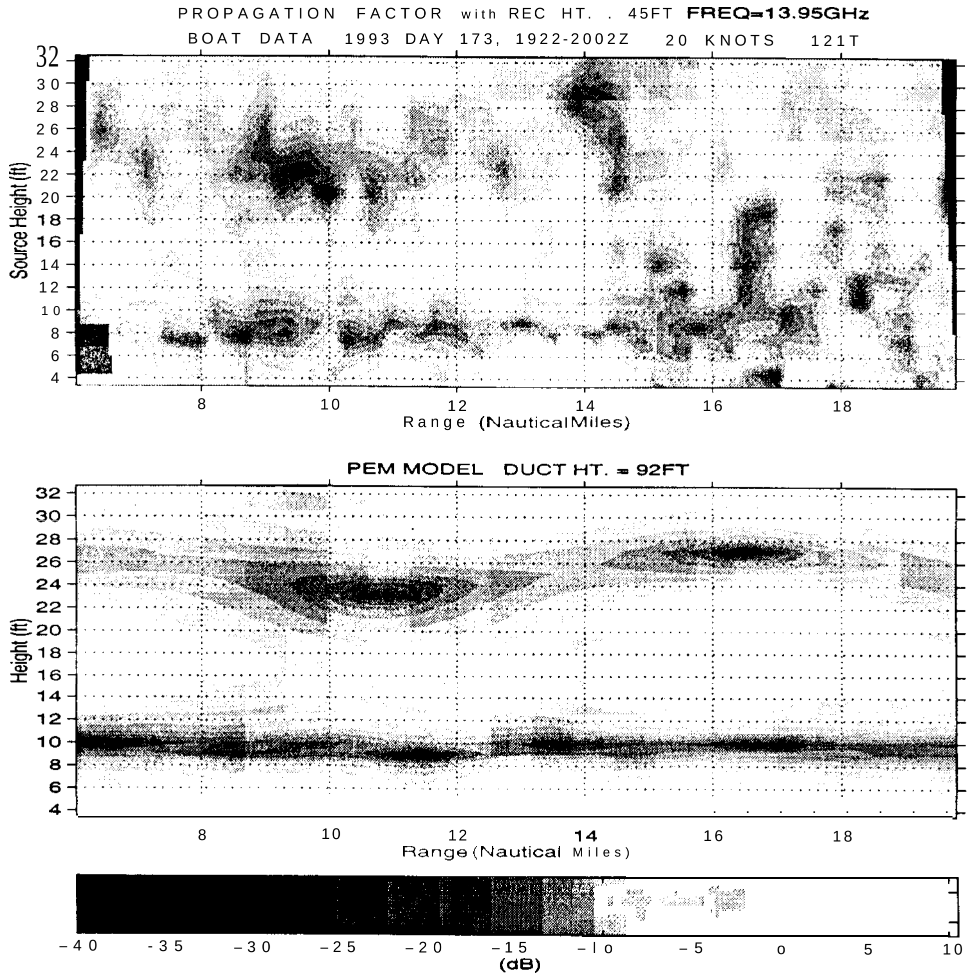

Figure 1. Horizontal Fade

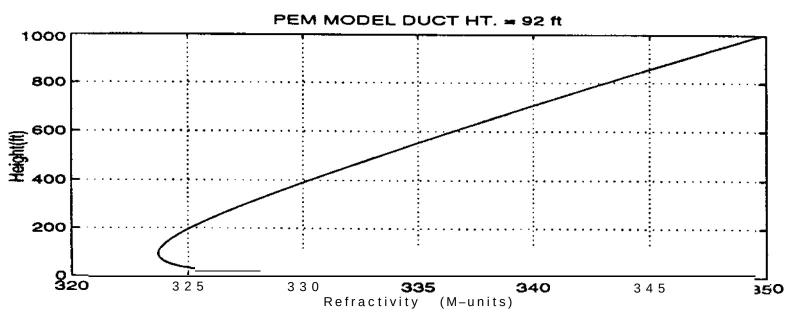

Figure 2. Refractive Profile for a 92 ft. Evaporation Duct

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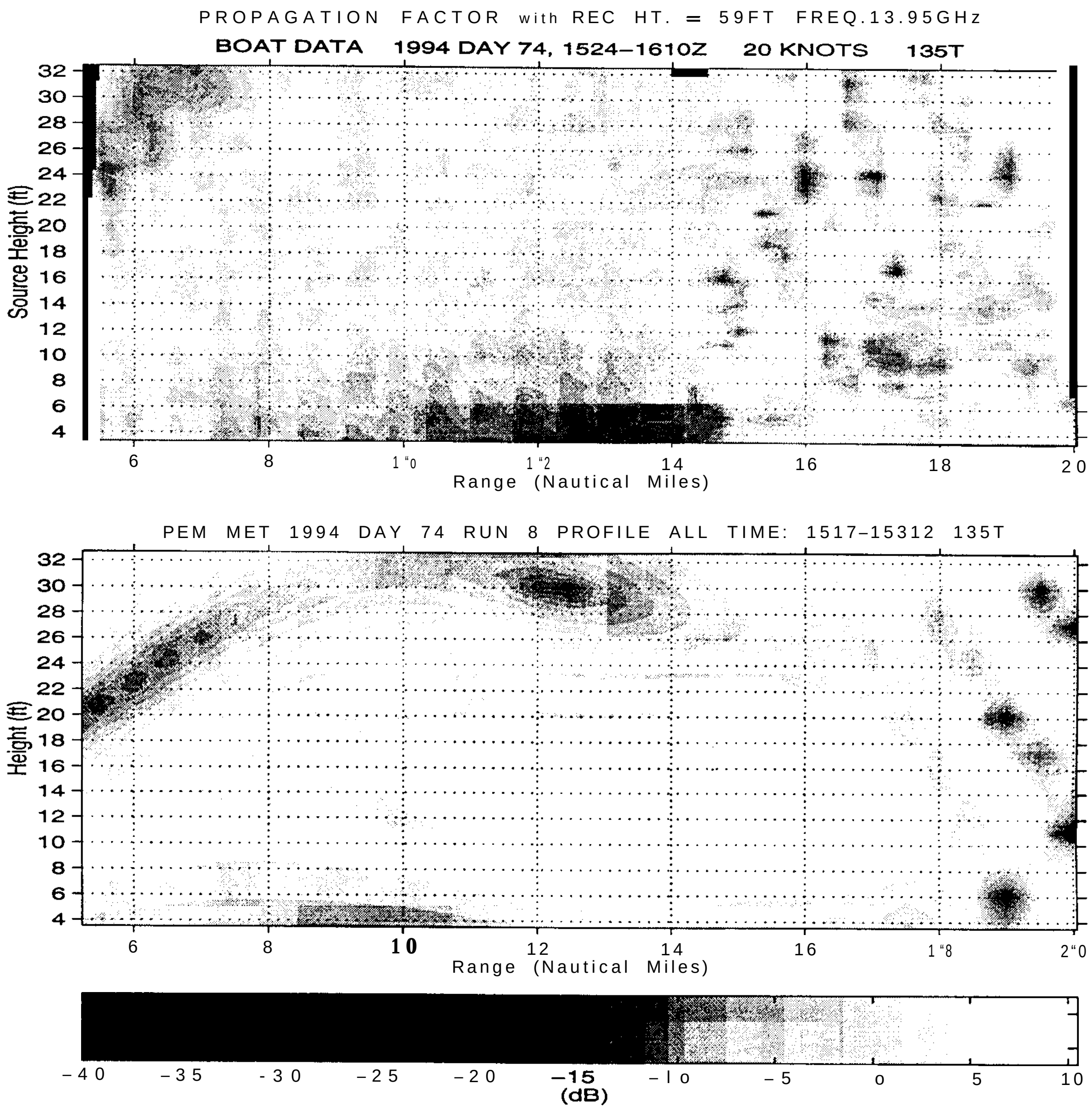

Figure 3. Propagation Due to a Surface Based Duct

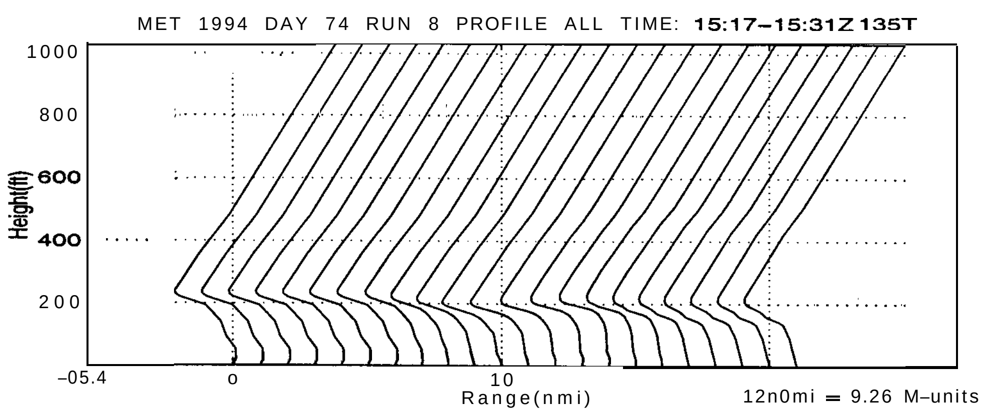

Figure 4. Measured Refractive Profile Versus Range

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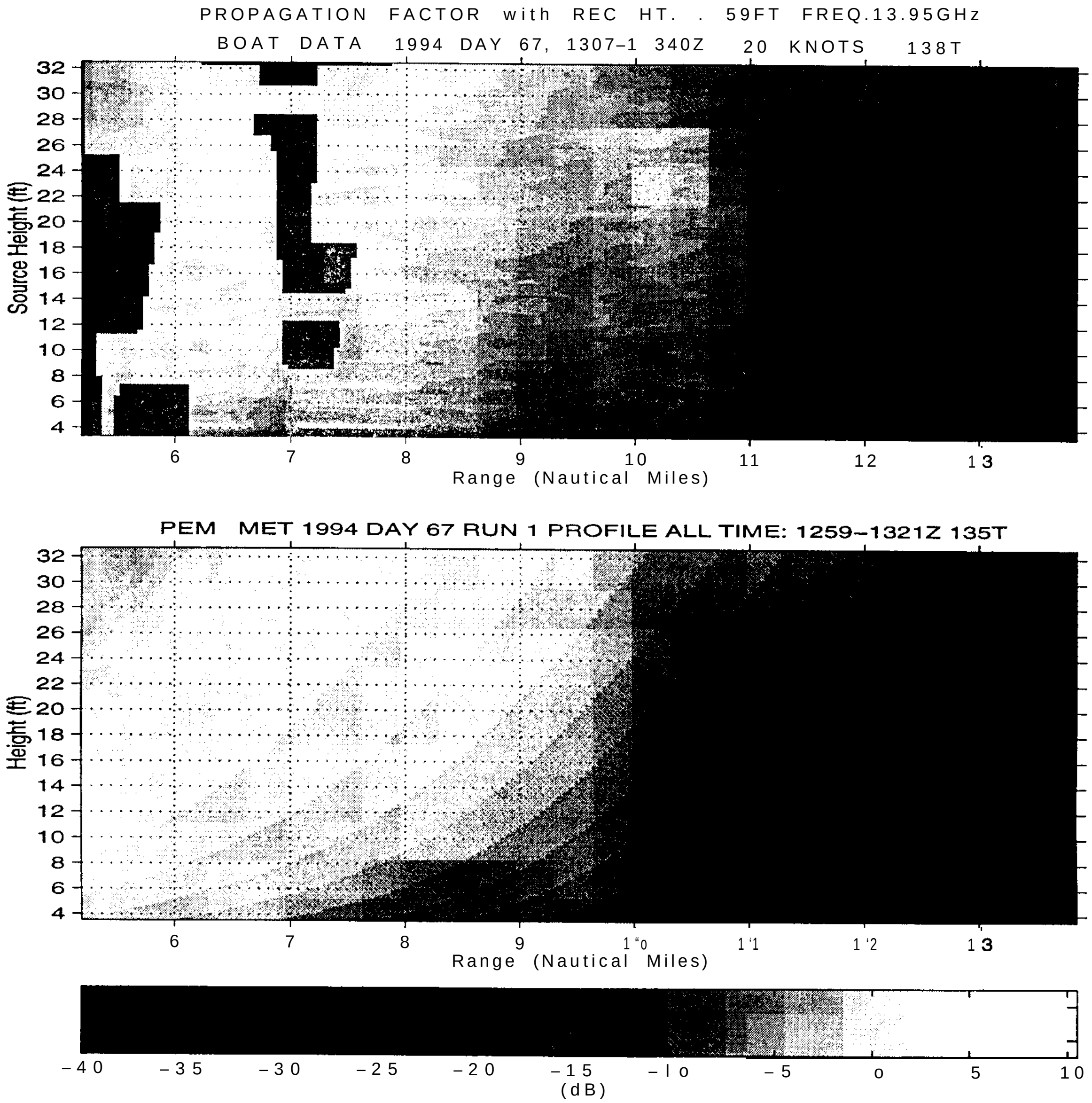

Figure 5. **Subrefraction**

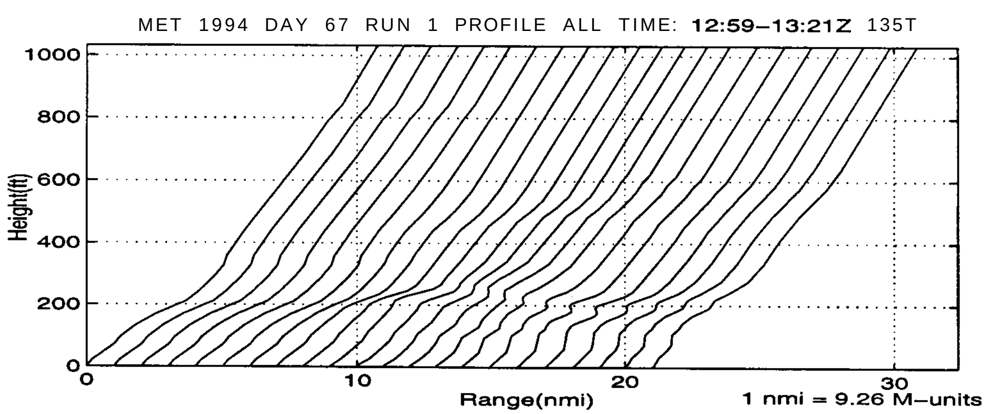

Figure 6. Measured Refractive Profile Versus Range for a **Subrefractive** Environment

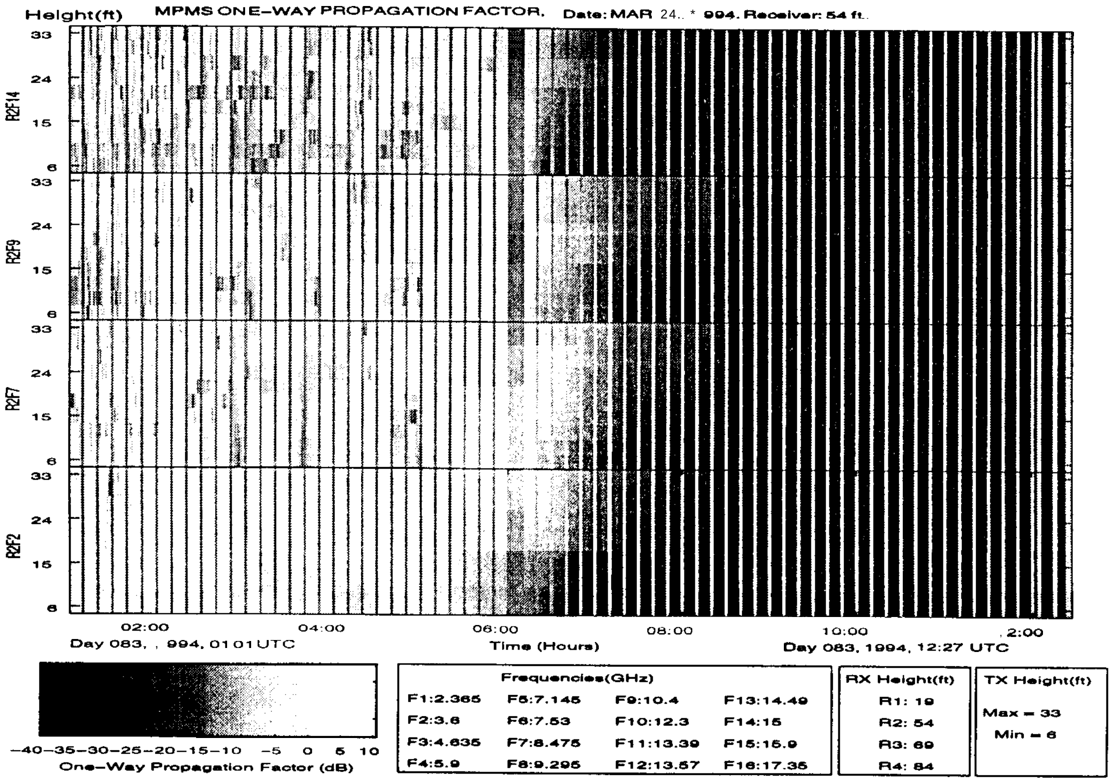

Figure 7. MPMS Measured Long Term Variability

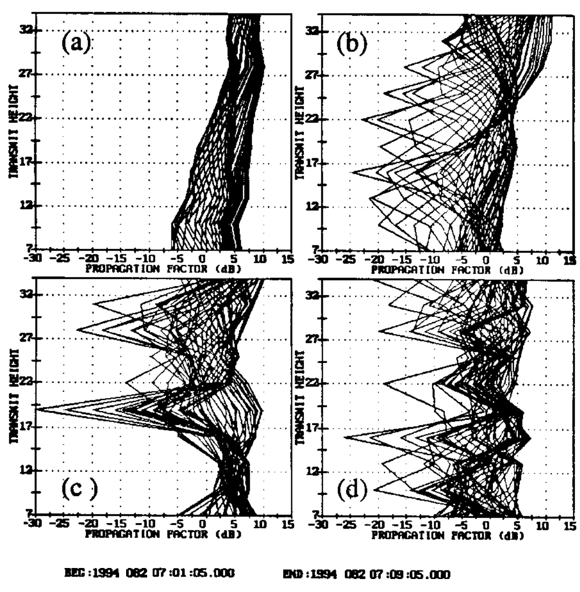

Figure 8. MPMS Measured Short Term Variability for Receiver at 84 ft: (a) 3.6 GHz (b) 5.9 GHz (C) 10.4 GHz (d) 15.0 GHz

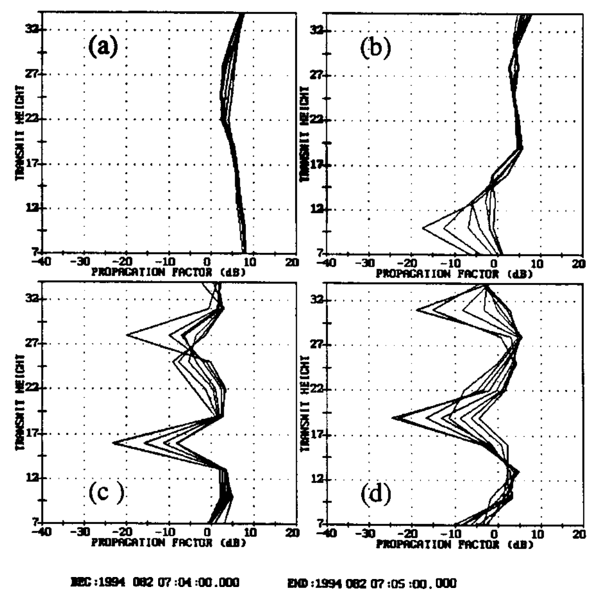

Figure 9. Frequency Effects On Null Filling Receiver at 54 ft: (a) 5.9 GHz (b) 8.475 GHz (c) 13.57 GHz (d) 17.35 GHz

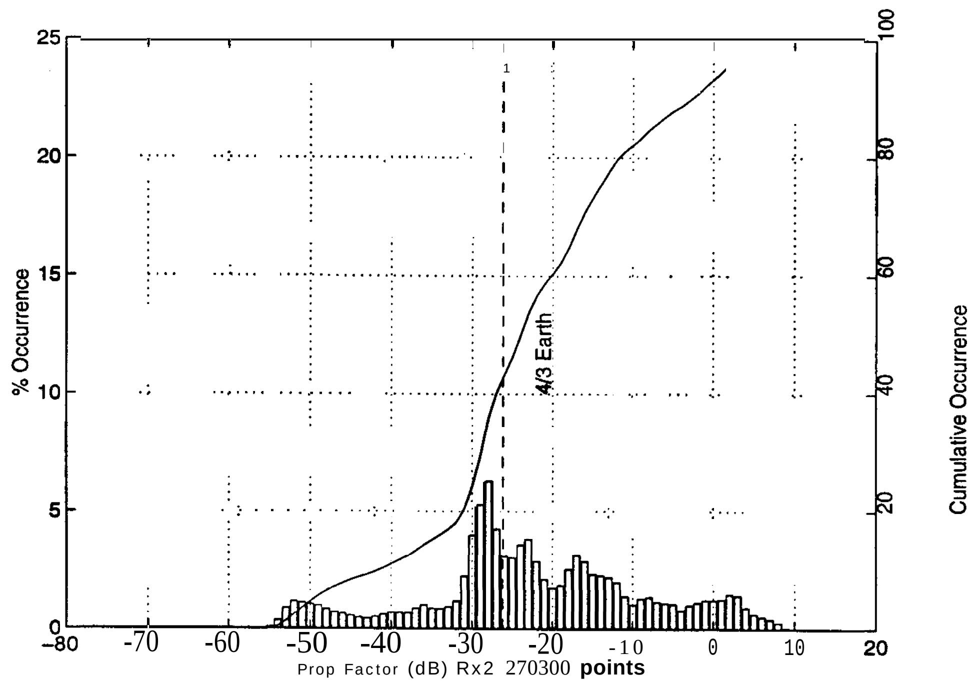

Figure 10. Propagation Statistic for the Receiver at 54 ft., Frequency 3.6 GHz, Target Height 15ft.

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